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From Green to Mean: Live Fuels Like to Misbehave

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Joint Fire Science Program
Fire Science Brief
RESEARCH SUPPORTING SOUND DECISIONS

South Canyon Fire, July 6, 1994.
Credit: Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-9.

From Green to Mean: Live Fuels Like to Misbehave

Summary

In July 1994, a low-intensity surface fire that had been burning on Storm King Mountain in Colorado suddenly intensified, shifting to the shrub canopy and rapidly advancing upslope. Caught off guard, 14 firefighters were trapped and lost their lives in the South Canyon Fire. A major contributing factor to this tragedy was lack of awareness of the behavior of fire in live fuels, in this case Gambel oak. Researchers have for decades sought to understand live fuel moisture variability and how it affects the behavior of fire in carefully controlled laboratory conditions, in prescribed fires, and in wildfires. The overriding question, one which has not yet been definitively answered, is this: Under what conditions will a surface fire enter green, moist canopy foliage to sustain a high-intensity, rapidly spreading crown fire? And given the importance of live moisture variability on fire behavior, how do we interpret live fuel moisture information gathered by satellite sensors or from field sampling for its application to describing fire behavior and predicting fire danger? A recent synthesis of our state of knowledge of fire behavior in live fuels, and an assessment of the utility and limitations of the models in widespread use, will be useful to those charged with interpreting the information and transforming it into sound management decisions. The delicate tradeoff is to ensure firefighter and public safety while effectively suppressing or containing wildfire or planning prescribed burns.

Key Findings

- In assessing fire behavior and predicting fire danger, live fuel moisture is one of the most difficult variables to measure and interpret.
- Live fuels resist fire spread until the fuel and fire conditions reach a critical threshold. Exceeding this threshold results in a sudden transition from no canopy fire spread to high intensity fire spread.
- The two methods of assessing live fuel moisture—satellite sensing and field sampling—have specific drawbacks that need to be understood before reliable fire behavior predictions can help ensure firefighter safety.
- The computer model on which all current systems are based—the Rothermel surface fire spread model—includes live fuel moisture; however the Rothermel model does not reliably describe the heat transfer and combustion processes necessary to predict live fuel behavior.

Introduction

On July 6, 1994, a lightning ignited fire on Storm King Mountain in Colorado claimed the lives of 14 firefighters. For three and a half days, the firefighters dealt with a low-intensity surface fire backing downhill. Evidence from the scene of the South Canyon Fire indicated that the firefighters were caught by surprise as the fire spread up the canyon and into the green canopy of the dense Gambel oak vegetation.

Strong, turbulent winds that developed that afternoon swept the fire quickly upslope, and burning embers sparked spot fires that increased both fire intensity and rate of spread, leaving the firefighters little time to escape. Investigations into the cause of this tragedy concluded that the firefighters did not anticipate the high intensity fire behavior burning through the live, green Gambel oak canopy. The fire had reached the canyon bottom and then burned up the steep slopes aided by strong winds. These conditions sustained the high intensity fire spread in the live, relatively moist, green Gambel oak foliage.

The fire environment triangle

Fuels, weather, and topography—the three legs of the fire environment triangle—comprise the principal factors that determine fire behavior. When quantitatively described, these basic components are fed into existing models to assess fire behavior and predict fire danger. In the early 1970s, a mechanical engineer, Richard C. Rothermel, at what was then the Northern Forest Fire Laboratory in Missoula, Montana, developed equations to predict fire spread. The Rothermel surface fire spread model, on which newer and more sophisticated fire behavior and fire danger models are based, consisted of a fairly simple set of equations to predict rate of spread.

Rothermel was aware of the limitations of his modeling system. "The biggest shortcoming in the Rothermel model is that it was developed in a laboratory and only on dead fuels," says Matt Jolly, an ecologist at the Missoula Fire Sciences Laboratory. Of the more than 50 computer modeling systems that have built on the Rothermel model, most attempt to incorporate live fuels into the equations. "The models are based on a firm foundation for dead fuels and a shaky foundation for live fuels," Jolly says.

With support from the Joint Fire Science Program (JFSP), Jolly has presented an overview of the modeling systems available to managers concerned with fire behavior and fire danger and a synthesis of current knowledge of live fuel moisture. Jolly finds that despite decades of research, much remains to be learned about the contribution of live fuel moisture to fire behavior.

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Model behavior

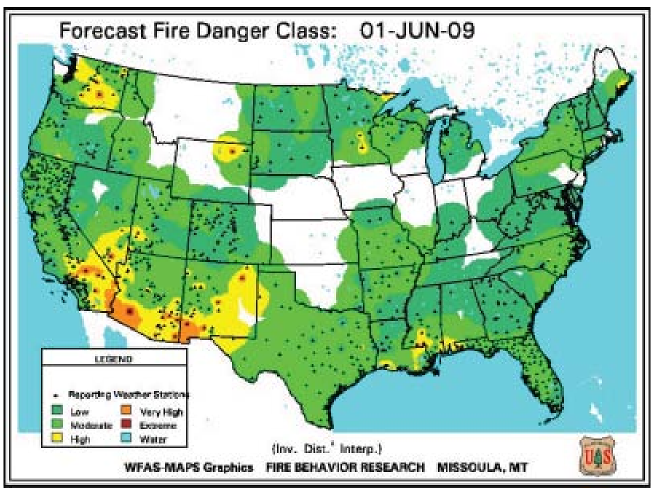
Worldwide, there are largely three operational modeling systems that were developed in Canada, Australia, and the United States. The Canadian and Australian systems are based on direct observation of prescribed and wild fires and incorporate estimates of both fire danger and fire behavior into each model. The Australian systems—a forest fire danger meter, a grassland fire danger meter, and a grassland fire spread meter—assess seven fuel types, including grasslands, open and closed forests, and woodlands. Live fuels are incorporated into these systems based on a fairly simplistic estimate of the degree of curing of fine herbaceous materials, that is the amount of dead grassy material in the sward, which consists of live grass, dead thatch, and grass roots.

The Canadian Forest Fire Danger Rating System was developed from observation of experimental and wildfires based on weather, observed fire behavior, and dominant cover type—forest, slash, or grassland. Analysis of live foliar moisture content and height of tree crown help determine the critical threshold at which a surface fire will spread to the crown, and fire is categorized into three types: surface fire, intermittent crown fire, and continuous crown fire. One drawback to this system is that foliar moisture content is measured in the canopy foliage, not in live surface fuels, where most fires start. For lack of a more sophisticated way to measure moisture content in the understory, the Canadian system, like the Australian systems, also uses a simplified measure of curing over the fire season.

In the United States, models are divided into two categories: those that predict fire behavior and those that assess fire danger. Both systems are useful management tools to plan for prescribed burns, foresee the likelihood of wildfire, and make critical decisions to ensure the safety of firefighters and the public.

Fire behavior systems use mathematical models to predict length of flame, rate of spread, and height of scorch. BehavePlus, one of the most widely used models, is a freeware program that can be downloaded to a personal computer and used to plan prescribed fires, assess fuel hazard, and predict the behavior of wildfire. It is relatively user friendly and is updated on a regular basis. “It is the best tool right now for planning prescribed fires as well as assessing wildfire,” Jolly says, “but fire managers need to know the limitations and understand the sensitivities of inputs and how that changes the outputs before they apply it to prescribed or wildland fire.”

The National Fire Danger Rating System uses a set of indices to predict the relative danger of wildfire based on daily and seasonal calculations of fuel and weather conditions. It takes a “worst-case” approach to information gathering by measuring conditions when fire danger is normally highest, at mid-afternoon, mid-slope, on southern to southwestern exposures, and in the open.



Fire danger class map for June 1, 2009. Credit: Derived from the U.S. National Fire Danger Rating System and generated by the Wildland Fire Assessment System.

FireFamilyPlus is a Windows-based software program that uses daily historical weather information and indices of fire danger based on archived data to analyze fire weather and fire danger. This information is used to plan management actions such as restricting access to fire-prone areas, banning campfires, deciding the best time for prescribed burns, or planning ahead for response to probable wildfires.

The Wildland Fire Assessment System (WFAS) is an Internet-based system accessible from any computer terminal. WFAS collects data from more than 1,800 weather stations across the country and from weather satellites maintained by the National Oceanic and Atmospheric Administration (NOAA) to produce national and regional maps of fire danger throughout the fire season.

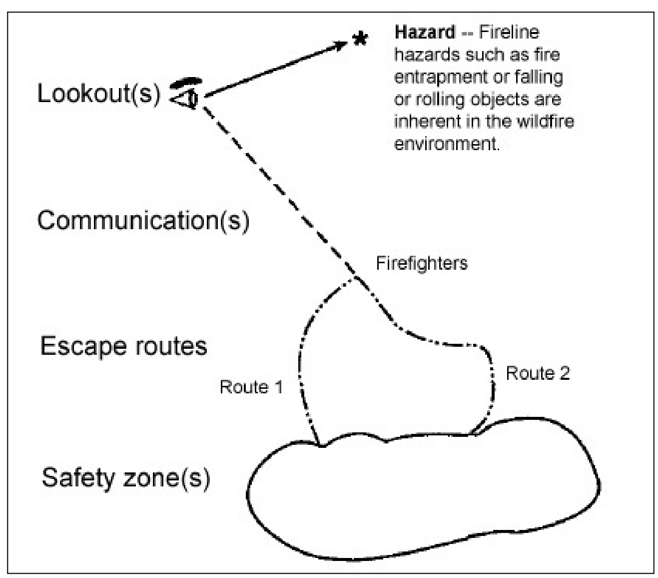
There is some risk, however, that these models may give decision makers and firefighters a false sense of security. “There are serious implications for making decisions based on computer-calculated values,” Jolly cautions. “People tend to use these numbers as absolute thresholds to determine the optimum time for a prescribed burn or to calculate a safety zone.”

Safety zone

Jolly and other researchers have found that small changes in live fuel moisture may cause dramatic changes in flame length and fire behavior. Moreover, how fuel models include live fuels can influence fire behavior predictions.

Jolly, using 13 older fuel models and 40 newer fuel models, all created for the Rothermel fire spread model, ran simulations across the entire range of live fuel moistures from 30–300 percent, keeping all other environmental parameters constant, to predict the surface fire spread rate, flame length, and Byram’s fireline intensity. He found that slight variations in the way live fuels are weighted resulted in different sensitivities of any particular model to predict fire behavior. In general, the newer models take better account of the proportion of live herbaceous materials and fine dead (one-hour time lag) fuels and are more sensitive to changes in live fuel moisture.

To estimate a firefighter safety zone, Jolly, using BehavePlus, found that a very slight decrease in fuel moisture, from 110 to 100 percent, causes an increase in flame length from 4.8 feet to 16.2 feet. In summer, 90–100 percent moisture content is common in herbaceous live material. If moisture content falls from 110 to 100 percent, the safety zone would need to be 2.3 times wider than predicted for a moisture content of 110 percent. In practice, however, it’s difficult to instantly assess small changes in fuel moisture that may occur due to changes in atmospheric conditions and therefore to estimate a safety zone in any particular situation.

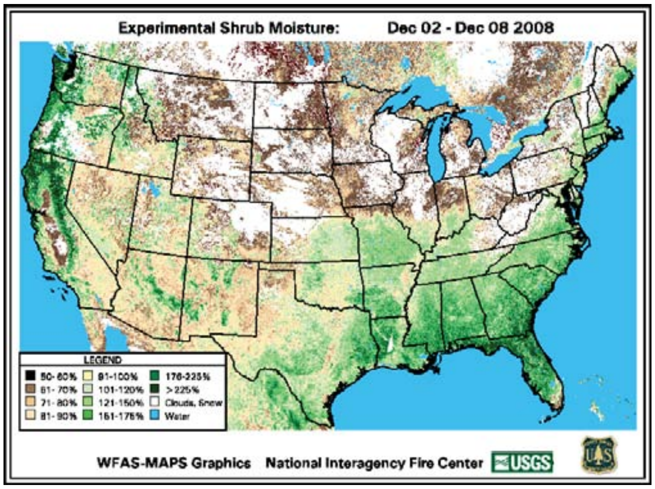


Credit: USDA Forest Service, Fire Management Notes, Vol. 52, No. 4, 1991.

Remote sensing

Information on live fuel moisture is gathered in two ways: remote satellite sensing and field sampling, also called ground truthing. Neither method is foolproof.

Satellite images are used to assess the seasonal life-cycle events—that is, the phenological state—of live vegetation by measuring the wavelength of light reflected by plants from the Earth's surface. These sensors show how "green" the vegetation is, and that can be a poor indication of how much moisture a plant contains. "How green the leaf is doesn't change, but the moisture content may change," Jolly says. In short, there is no perfect correlation between the spectral data and moisture content.



Relative Greenness image from July 1 to July 7, 2008. Credit: Wildland Fire Assessment System.

In the continental United States, greenness maps—the Relative Greenness Maps and Departure from Average Maps—are accessed via the Internet. One limitation for forests in using these remote sensing platforms is that satellite images largely "see" the tree canopy, not the forest floor. "Most of the signal comes from the overstory and just a little from the understory," Jolly says. "The understory is where the fire starts."

A widespread misconception is that in spring, plants are green and moist, and that fire danger increases in a straightforward way as the plants mature and then dry out. Moisture content, however, is in a constant state of flux on a daily and seasonal basis. Jolly describes a phenomenon, known as spring dip, that occurs when, through photosynthesis, the plant is putting its energy into storing carbohydrates and other complex nutrients, and the mass of the foliage increases, thereby reducing the proportion of moisture.

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Ground-truthing

The second means to measure live fuel moisture is by gathering vegetation and analyzing moisture content in the lab. This method, which was originally used to sample vegetation in fire-prone southwestern ecosystems such as California chaparral, is time consuming, expensive, and hard to do reliably.

In addition, live fuel moisture is difficult to measure from random field sampling. "To ensure accuracy, the number of samples required is astronomically high," Jolly says, and the samples collected are hardly ever measured without unaccountable error. "Nobody can tell you what the range of moisture content is with complete accuracy."

"Since 1972 we have had the ability to include live fuel moisture content in our fire spread models," says David Weise, a supervisory research forester with the Pacific Southwest Research Station in Riverside, California. "The way things are averaged in a fuel model, the moisture content of the dead fuels gets the most weight." However, none of the fuel models are composed completely of living material. The fire spread model assumes dead fuel is required for spread and the live fuels only contribute to fire spread. Several researchers have shown that fire will spread in fuel beds made of 100 percent live fuel.

For more than 15 years, Weise has conducted laboratory experiments on live fuel moisture, and he still remains puzzled by some of the findings. "Dr. Tom Fletcher and his students at Brigham Young University have found in leaf ignition experiments that there is a wide range of temperatures at which a green leaf will ignite," he says. Nearly 40 years ago, the noted fire behavior scientist Frank Albini found that as a leaf is exposed to an ignition source, some of the water evaporates, yet combustion occurs before all the moisture is gone.

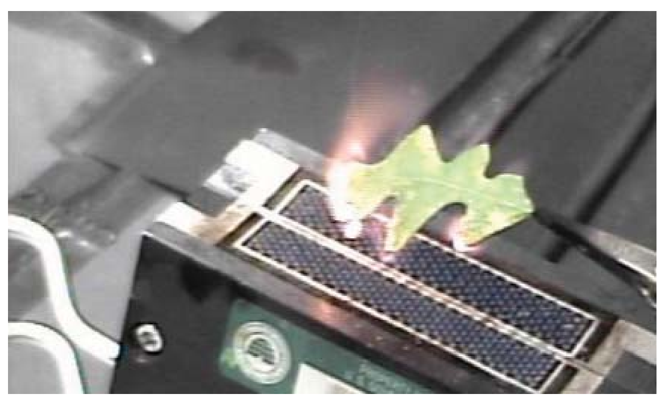

Photo of a burning Gambel Oak leaf (initial moisture content 80 percent) just after ignition. Credit: Dr. Thomas Fletcher and co-workers at Brigham Young University.

In his lab work, Weise has also examined the effects of very small changes in wind speed on ignition at the fuel bed level, mostly at the low end of fire behavior. "We have learned at the laboratory scale that it doesn't take a whole lot of wind to cause fire to spread through living vegetation, 2 to 3 miles an hour," Weise says.

South Canyon revisited

Jack Cohen, a research physical scientist in the Fire, Fuel, and Smoke Science Program at the Missoula Fire Sciences Laboratory, was a member of the research team that examined how fire behavior occurred on the South Canyon Fire. An initial report was issued by the Interagency Management Review Team in 1995. A more extensive fire behavior research report followed in 1998. "What seemed confounding is that the fire burned down through live vegetation for three and a half days without causing high intensity fire spread. We asked ourselves, how could this happen? How did the fire burn under the live canopy for days and then quickly spread through the live canopy at high intensity? It's a threshold increase in fire intensity, going from surface burning to canopy burning with little apparent transition," Cohen says.

The behavior of fire in live and dead fuels at different moisture contents also continues to perplex researchers. "With a dead fuel, a stick that is just dead cellulose, you cannot get it to absorb more than about 30 percent moisture, and typically a dead fuel bed at that moisture content doesn't burn." The moisture content of live conifer foliage, however, is three times that much, 80 to 100 percent, and yet fire spread can occur.

"With a dead fuel, a stick that is just dead cellulose, you cannot get it to absorb more than about 30 percent moisture, and typically a dead fuel bed at that moisture content doesn't burn." The moisture content of live conifer foliage, however, is three times that much, 80 to 100 percent, and yet fire spread can occur.

Fire in the canopy of live fuels also burns only one way: at high intensity. "It can't burn any other way," Cohen says.

Despite the limitations of current models, they remain useful for predicting fire danger and fire behavior. Jolly cautions, however, that there are very serious safety implications for making decisions based on computer-generated values that attempt to incorporate live fuel moisture as a variable. "Managers need to know the limitations of modeling systems before they apply them to prescribed fire or wildfire," he says.

Management Implications

- Small changes in live fuel moisture content inputs to current fire models can produce large increases in flame length and rate of spread with uncertain reliability.
- Underestimating live fuel moisture can produce overestimates of fire behavior and result in unnecessary increases in the cost of fighting fire. Conversely, overestimating fuel moisture can underestimate potential fire behavior and increase the risk to firefighters.
- Fuel moisture content is difficult to estimate from small samplings because of the wide range of variability. Decisions based on larger samples increase the precision of the estimate.
- Information from greenness maps or field observation should be used with caution since moisture content and relative greenness are not perfectly correlated.

Further Information: Publications and Web Resources

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Scientist Profiles

W. Matt Jolly is an Ecologist in the Fire, Fuel and Smoke Science Program at the Missoula Fire Sciences Laboratory of the Rocky Mountain Research Station in Missoula, Montana. He received a Ph.D. in Forestry from the University of Montana. Matt's main research interests center around linking plant physiological processes with combustion and fire behavior characteristics of live fuels.

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David R. Weise is a Supervisory Research Forester with the Pacific Southwest Research Station Forest Fire Laboratory. His current research focuses on models for fire behavior and fuel treatment, including fire spread models, fuel moisture models, and landscape level planning models.

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Letter to JFSP:

CANADA, HEY?:
Clarifying the Development and Structure of the Canadian Forest Fire Danger Rating System

I recently read Fire Science Brief Issue 67 (September 2009) titled *From Green to Mean: Live Fuels Like to Misbehave*. There are three comments made on page 2 of this publication that would give the uninformed reader the opinion that the Canadian Forest Fire Behavior Prediction (FBP) System sub-component or module of the Canadian Forest Fire Danger Rating System (CFFDRS) was somehow neanderthal like in its development and structure:

- "The Canadian Forest Fire Danger Rating System was developed from observation of experimental and wildfires based on weather, observed fire behavior, and dominant cover type – forest, slash, or grassland".
- "One drawback to this system is that foliar moisture content is measured in the canopy foliage, not in live surface fuels, where most fires start".
- "For lack of a more sophisticated way to measure moisture content in the understory, the Canadian system … uses a simplified measure of curing over the season".

With respect to the first comment, it is true that the system is built upon outdoor experimental fires coupled with data obtained from operational prescribed fires and wildfires. The latter have been particular useful at the extreme end of the fire behavior scale, where experimental fires have been difficult to schedule and manage. The environmental conditions associated with each fire are documented. The empirical data is then analyzed and explained using simple mathematical models and correlation techniques. For a complete in-depth technical description of the FBP System, please refer to Forestry Canada Fire Danger Group (1992) and Wotton et al. (2009).

Now regarding the second comment. Foliar moisture content is indeed one of the inputs used in determining the onset of crowning conifer forest. While there is some seasonal variation in the amount and moisture content of live understory fuels in Canadian forests, the so-called "green surface fuel effect" does not show nearly as strong a trend as observed in the United States. This is not to say that influence on fire potential is completely ignored. The way in which it is handled in the FBP System is through the provision of several fuel types for which there is both a "leafless" condition for spring and fall as well as a "green" state for summer. For further information, I would suggest having a look at Alexander (2010).

Finally, as for the third comment. In the grassland fuel types found within the FBP System, there is a requirement to provide an estimate of the "degree of curing" (i.e., the proportion of dead material relative to the total amount) in order to predict rate of fire spread and intensity (Taylor et al. 1997). The degree of curing is a very fundamental physical fuel characteristic in grasslands. See, for example, Cheney and Sullivan (2008) for further information.

For a broad overview of the CFFDRS see Taylor and Alexander (2006) and for further information I would suggest consulting the following: http://www.frames.gov/cffdrs

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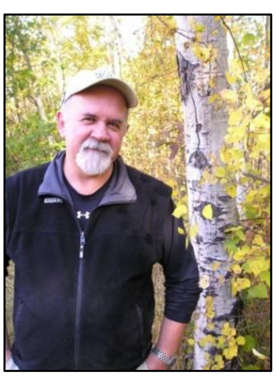
Dr. Alexander retired from the Canadian Forest Service in November 2010 following nearly a 35-year career. At the time, he was a Senior Fire Behavior Research Officer stationed at the Northern Forestry Centre in Edmonton, Alberta. Dr. Alexander is considered a leading authority on the Canadian Forest Fire Danger Rating System.



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